EARTH SURFACE PROCESSES AND LANDFORMS
Earth Surf. Process. Landforms **38**, 106–110 (2013)

Published online 22 November 2012 in Wiley Online Library
(wileyonlinelibrary.com) DOI: 10.1002/esp.3362

ESEX Commentary

21st century climate change: where has all the geomorphology gone?

Stuart N. Lane*
Faculté des geosciences et de l'environnement, Université de Lausanne, Switzerland

Received 10 October 2012; Revised 24 October 2012; Accepted 25 October 2012

*Correspondence to: Stuart N. Lane, Faculté des geosciences et de l'environnement, Université de Lausanne, Switzerland. E-mail: Stuart.Lane@unil.ch

ESPL
Earth Surface Processes and Landforms

ABSTRACT: This Commentary draws together recently published work relating to the relationship between climate change and geomorphology to address the surprising observation that geomorphic work seems to have had little impact upon the work of the Intergovernmental Panel for Climate Change. However, recent papers show that methodological innovation has allowed geomorphological reconstruction over timescales highly relevant to late 20th century and 21st century climate change. In turn, these and other developments are allowing links to be made between climatic variability and geomorphology, to begin to predict 'geomorphic futures' and also to appreciate the role that geomorphic processes play in the flux of carbon and the carbon cycle. Copyright © 2012 John Wiley & Sons, Ltd.

KEYWORDS: climate change; geomorphology; earth surface processes; Intergovernmental Panel on Climate Change

Introduction

This Commentary introduces a virtual issue of *Earth Surface Processes and Landforms* concerned with geomorphic contributions to our understanding of the relationship between global climate change and geomorphic processes, landforms and impacts. My starting point is an observation from the Intergovernmental Panel in Climate Change (IPCC, 2007). The IPCC's Working Group II looked at possible impacts of climate change, including upon the freshwater environment in general and erosion and sediment transport in particular (Section 3.4.5). In relation to sediment transport, 12 papers are referred to and most of these refer to soil erosion. The IPCC concludes explicitly that not much work has been done on the impact of climate change on sediment loads in rivers and streams. Geomorphology appears very briefly in the IPCC's discussion of particular environments (e.g. Section 4), and more strongly in relation to coastal impacts both generally (e.g. Section 6) and in specific regions. Reading the IPCC, one might wonder where all the geomorphology has gone, not least because the need to quantify and to predict climate change impacts on geomorphic systems has not been lost on geomorphologists. For instance, Lu *et al*. (2010) provide a clear call for source-to-sink geomorphic analyses that are able to understand just how the great mountain systems of the Asian subcontinent will respond to climate change and so drive the flux of sediment to coastal zones.

Geomorphology has a long history of quantifying landscape response to environmental change (see review in Macklin and Lewin, 2008), a history that has benefited enormously over the last two to three decades from the development of new dating methods. Similarly, geomorphological information can be central to the reconstruction of palaeoenvironments and climate change (Macklin and Lewin, 2008; Thomas, 2013). Over the timescales of centuries to millennia, such work has shown the complex linkages between climatically-driven and human-driven (e.g. land-use change) impacts of environmental variability (Colombera and Bersezio, 2011). But, a simple question remains: what kinds of contributions should geomorphology be making to wider debates regarding global climate change? In introducing this virtual issue, I reflect upon three broad themes clear in publications relating to climate change recently published in *Earth Surface Processes and Landforms*: (1) the growing ability to understand the relationship between short-term (annual to decadal) climatic variability and geomorphic systems; (2) the difficulty and potential of predicting change in geomorphic systems over the 21st century; and (3) the recognition that geomorphic science has an important contribution to make in understanding the impacts of surface processes upon carbon flux and hence carbon mitigation strategies.

The Geomorphic Signature of High Frequency Climatic Variability

There is an important history of using geomorphic evidence to quantify long-term environmental change, the classic being Holocene flood histories (Macklin and Lewin, 2003; Jones *et al*., 2008; Harden *et al*., 2010). However, as we approach the timescales of decades and years, we enter a period where: (1) geomorphic processes become progressively more influenced by the growing intensity of human activity (Lewin, 2013); (2) certain geochronological techniques yield insufficient dating precision; and (3) systematic landscape signals of climate change impacts may become confused with natural variability (Church, 1996). The last two of these points are closely related and it is here that innovation in geomorphic methods is both enabling shorter timescales of investigation but also allowing us to appreciate the natural variability against which human impacts will need to be judged.

A critical example of methodological innovation relates to dendrogeomorphology, which has shown that not only do trees provide a chronological date since establishment but also valuable information on geomorphic processes themselves. For instance, Arbellay *et al.* (2010) showed that it was possible to date the occurrence of debris flows and their spatial structure in the Illgraben system, Switzerland between 1965 and 2007 by interpreting the records of 154 injured broad leaved trees. Not only did this reveal useful information regarding the frequency of temporal activity in the Illgraben, extending data into periods when these flows were not routinely monitored, they also revealed useful information of debris flow dynamics themselves (e.g. spread and travel distance). Savi *et al.* (in press) used dendrogeomorphological reconstruction for an Alpine catchment to show that hillslope–channel coupling became dependent on more extreme events with distance down through the catchment. Colombera and Bersezio (2011) used similar methods, along with aerial image interpretation, to show how over the last 200 years, most of a Last Glacial Maximum alluvial fan surface had been reworked during one of two extreme debris flow events. These extreme events delivered sediment, causing fan steepening and aggradation. Events with smaller magnitude and shorter return period lead to entrenchment and narrowing, also linked to fan toe incision.

These and other methodological developments have allowed us to collapse the timescales of geomorphological reconstruction. In turn, they bring to the fore a new concept: Historical Range of Variability (HRV). With many environmental phenomena, as the temporal resolution of measurement is reduced, so the variance of the phenomena increases. Thus, when faced with a noisy geomorphological signal, the question becomes how much of the measured variance is expected, natural variability, and how much is indicative of genuine change. One way to approach this is to set measured variability against past or historical variability. HRV is the subject of a forthcoming Special Issue in *Earth Surface Processes and Landforms*. Although HRV must necessarily remain a constructed concept (for instance, it requires us to specify the timescale over which that variability is determined, itself driven by the kind of methodological developments described above) it provides a template against which systematic impacts of climate variability and climate change can be judged. For instance, Petterson *et al.* (2010) related the sedimentation records in lake varves for an undisturbed forest watershed to identify the range of variability in sedimentation processes. Layzell *et al.* (2012) were able to combine a range of methods to quantify different types of Holocene river channel adjustment, including phases of deposition and incision. With this variability established, they were able to show that the system was exceptionally sensitive to climate change driven changes in sediment supply. The landscape response, however, was equally impacted upon by the legacy of effectively 'out-of-climate-equilibrium' sediment conditions, in terms of a legacy of glacial deposits available for stream reworking. This kind of work is an important reminder that many of our landscapes, especially those in mid-latitudes and high latitudes are currently out of equilibrium with current climate even before the onset of rapid climate change. But, the methods that we have to distinguish change from natural variability continue to need refinement. For example Korup *et al.* (2012) show that we need to be much more sophisticated in how we search for climate change signals in landslide inventories as our methods have not necessarily developed in ways that are sensitive to statistical non-stationarity. Korup *et al.* show that the act of fitting distributions to such inventories may mask possible climate change signals.

Given our ability to quantify variability over shorter timescales, a further trend is emerging: the ability to evaluate, across a range of different environments, geomorphic forcing by climatic variability at the scale of years to decades. For instance, Tote *et al.* (2011) showed for a river basin in northern Peru that El Nino Southern Oscillation (ENSO) was responsible for the flushing of stored sediment, reversed during post-ENSO periods. Brook *et al.* (2011) show that the area of small glaciers fluctuates in relation to the forcing of ablation by regional atmospheric circulation, notably the ENSO but also the Interdecadal Pacific Oscillation. Bauch and Hickin (2011) report that increases in the magnitude and duration of the annual flood is responsible for a dramatic increase in channel activity in the Squamish River, Southern British Columbia, notably in terms of erosion, a change that that they attribute to the intensification of late season Pacific storms. Thomas *et al.* (2011) have been able to show links between the North Atlantic Oscillation (NAO) and erosional/depositional shoreline response in South Wales, UK. Clarke and Rendell (2010) used three decades of erosion measurement to show that the persistently positive values of the NAO between the 1980s and 2000 were correlated with reduced winter rainfall and that this had reduced Mediterranean badland erosion rates in Italy. Notwithstanding possible increases in the frequency of extreme rainfall events, they note that climate scenarios suggest further reduction in annual rainfall and hence erosion rates. These kinds of studies don't just identify new types of coupling between atmospheric variability and geomorphic response: they also challenge our understanding of existing ones. Thus, Lu *et al.* (2011) challenge the view that Asian monsoon related precipitation can be identified in records from the Loess plateau, China as dust accumulation rates are decoupled from the extent of active Aeolian sand in dune systems.

Notwithstanding the observed importance of the NAO above, Petterson *et al.* (2010) were unable to identify an NAO in their lake varve records for an undisturbed forest system, although the impacts of solar forcing appeared to be present. This points to the need to think carefully about how climate variability will propagate through geomorphic systems, ones that operate as a filter that can both magnify and smooth climate forcing. For example, Savi *et al.* (in press) showed that even if climate change impacts upon sediment delivery, sediment load will be a function not just of sediment sources but also the ways in which those sources are coupled to the drainage network and are, in turn, transported through it. As Colombera and Bersezio (2011) showed, the magnitude of an event necessary for effective sediment transfer will differ between processes within a landscape, such that understanding landscape response to climate forcing will need consideration of both the magnitudes and the sequencing of events.

From Climate Change Impacts to Futures and Feedbacks

If progress is being made in establishing the linkages between climatic variability and geomorphic response, it is clear that somewhat less progress is being made in establishing how that variability might change during the 21st century and what this might mean for geomorphic processes, landforms and entire landscapes. A critical problem here appears to be the probability that such responses will be highly non-linear: a consequence of threshold dominated systems where the thresholds themselves evolve with the state of the system and in response to possibly small climate forcings. For instance, Huggel *et al.* (2012) consider climate change impacts upon landslide activity in Alpine settings. Here, landslides are thought to be ubiquitous under stable late Holocene climates but are argued to be particularly sensitive to climate warming because of non-linear responses of firn and ice to warming (notably albedo feedbacks), the possible warming at the interfaces between ice/sediment and bedrock, the retreat of glaciers leading to exposure of more erodible sediment, in addition to temperature and precipitation effects on event generation.

However, we can identify two broad areas of progress. The first is grounded firmly in the fundamental scientific basis of geomorphic–climatic coupling, from which it is possible to conceptualize how, for instance, temperature change might impact upon process rates. Anderson *et al.* (2013) considered weathering processes in the zone beneath mobile regolith, an important control upon the rate of mobile regolith production. They found that in landscapes with typical regolith residences times of 10 000 to 100 000 years, climatic variability modulated both deep weathering and sediment flux, the former sensitively conditioned by aspect. Critical was the degree to which it was possible to cause frost damage, something that is likely to respond quite sensitively to climate amelioration and deterioration. Dendrogeomorphic methods have confirmed the dominant role played by freeze–thaw cycles according to Silhan *et al.* (2011), who dated 989 rockfall events in the Carpathians to provide a 78 year record of rockfall activity and which they linked to climatic data.

The second area of progress relates to the prediction of geomorphic processes, landforms and landscapes in response to changing climate. Predicting the non-linear behaviour described by many geomorphologists will be difficult. But is it any more difficult than the climate science, ecosystem science or any other kinds of science where 'futures' work has become more dominant? The use of numerical models to quantify linkages between climate forcing and geomorphic response, and then to drive such models with climate futures, is much less developed than empirical studies focusing upon past climatic variability. But it is developing. For example, Leyland and Darby (2009) consider coastal gully response to Holocene sea level rise using a landscape evolution model. They show that the balance between sea level driven cliff retreat and knickpoint recession rate controls the development of gully networks. As rates of sea level rise are forecast to increase over the 21st century, the survival of gully networks may be substantially reduced. Verhaard *et al.* (2010) explicitly sought to couple climate model predictions to an established model of tributary sediment routing. They found that in the absence of base-level changes, bed material delivery from tributaries to the St. Lawrence river (Quebec, Canada) is likely to increase, although this depends also on which climate model is used and the state of the river in terms of current aggradation or degradation. These effects become amplified if the base level also falls.

Verhaard *et al.* (2010) go a considerable way to addressing the lacuna identified by the IPCC (2007). We probably need many more studies of this kind so that we can start to tease out those environments where: (1) changing climate and changing climatic variability combine with; (2) those geomorphic systems that are especially sensitive; to produce (3) systematic landform and landscape responses to changing climate. As with all futures work, we need to accept that what arises is a set of scenarios for the future rather than a definitive prediction of what the future will be. It probably also needs a cultural acceptance of the value of modelling futures that we can neither see nor measure, by definition. Such an acceptance need not devalue the role that field enquiry plays in establishing how climate couples to geomorphic systems; nor in generating the historical datasets which through retrodictive modelling allow us to get more confidence in model predictions. But as the history of climate modelling has shown, models of the future, that are partial at best, incorrect at worst, can play a crucial role in stimulating both scientific enquiry and policy development. Perhaps the overriding lesson of climate modelling history is the need to produce models that capture a progressively larger number of ocean–atmosphere feedbacks. By analogy with this history, we might imagine that modelling geomorphological futures might proceed in the same manner as an ever-greater number of feedbacks are identified and appreciated. There is no doubt that as with the climate system, there will be some surprising geomorphic feedbacks out there. Bullard (2013), for example, notes that glacigenic sources of dust, for instance, could be much more significant than non-glacigenic ones if there is extensive ice sheet retreat. The critical challenge will be identifying such feedbacks and establishing their relevance at the spatial scales that geomorphological models are being applied.

Geomorphic Processes, Carbon Flux and Climate Change Mitigation

Perhaps one of the most interesting questions to emerge in geomorphic science in recent years is the potential role that sediment flux might play in nutrient cycles in general and in relation to carbon in particular. For instance, soil erosion from agricultural land could be both a source (through mineralization during transport) and a sink (through deep burial of soil rich in organic matter) (Kuhn *et al.*, 2009). This is why studies of the relationship between climate change and soil erosion are needed, not just because of potential impacts of climate change upon soil erosion, but because of what these impacts might mean in terms of carbon flux (Dymond *et al.*, 2010; Doetterl *et al.*, 2012). Such research must address three broad needs. First, classic studies on the controls of soil erodibility need to be extended to the question of soil carbon release. For instance, Novara *et al.* (2012) show that carbon release from soils depends upon soil compaction and the duration of exposure to rainfall, with greater carbon dioxide release with soils that are less compacted. Thus, under climate change, the impact on net soil carbon losses is likely to depend upon the balance between: (a) rainfall intensity driven increases; and (b) soil management driven changes; in soil compaction. Second, and more generally, studies need to attend to how human activities impact upon soil redistribution and in turn shape carbon flux. It is of particular interest because if soil management is implicated in carbon flux (such as linked to tillage erosion; Van Oost *et al.*, 2009) then soil protection may gain an additional rationale. It is a particular challenge because it is probable that soil management will evolve in response to climate forcing, implying that understanding the future net impact of climate change upon the carbon cycle will require us to predict the coupled evolution of social-human geomorphic and hydrological systems, something that is rarely seen in geomorphic enquiry. A notable exception is Wainwright and Millington (2010) who show that it is possible to use agent-based models to understand the coupled interaction and co-evolution of physical and social systems and the impacts of this interaction on sediment flux.

Third, there are particular questions relating to environments that act as critical carbon stores, such as peatlands (e.g. Worrall *et al.*, 2011). Geomorphic understanding of upland peatland dynamics has revealed that eroding peatlands are major sources of particulate organic carbon loss. However, the extent to which this loss is realized depends upon the fate of eroded carbon, the extent to which it is stored (Pawson *et al.*, 2012). Nonetheless, for mitigation purposes, geomorphic research is now actively factoring carbon exchange into the evaluation of landscape restoration processes: for instance, Clay *et al*. (2012) quantify the relationship between carbon pathways and hydrological processes in the restoration of blanket peat. In a very different environmental setting, Hilton *et al*. (2011) report on the role played by mass movements in the flux of organic matter and hence carbon. It is clear that geomorphic activity has the potential to be a significant driver of carbon flux in some environments, providing a critical imperative to factor carbon into long-established geomorphic questions.

Conclusion

It is clear from the manuscripts discussed in this Commentary that geomorphologists are making an extremely rich contribution to studies of major importance for understanding 21st century climate change. We can think of this in terms of research that is, perhaps at last, bridging two very different timescales: that of much longer landform evolution, the study of which has been revolutionized by new dating methods; and that of the established 'process' tradition, based upon continuous or near continual measurement using specially designed instrumentation. The former is of value over timescales of centuries and longer; the latter is rarely of use for anything more than the weeks, months or years during which funding has been available to maintain instrumentation. Methodological developments, coupled to innovative use of historical records (e.g. airborne imagery), are allowing us to reconstruct geomorphic systems over the timescales during which there has been rapid climate change (since the middle of the 20th century).

Forays into predictive numerical modelling, especially of the future, remain proportionately fewer. Perhaps this reflects a geomorphic obstinacy to the idea that landforms and landscapes are predictable. There may be reason here if geomorphic systems are really going to respond in complex and non-linear ways to changing climate (Huggel *et al*., 2012). But, as argued above, such responses have not prevented other disciplines from engaging in prediction and in ways that have stimulated both scientific research and policy development.

Finally, and perhaps most interestingly, are those manuscripts that are seeking to couple traditional geomorphologically-inspired questions (e.g. the controls on soil erosion) to other elements of the earth system, such as carbon storage and flux. It is clear that this is an area of fundamental science where geomorphic investigation has much to offer.

References

Anderson RS, Anderson SP, Tucker GE. 2013. Rock damage and regolith transport by frost: an example of climate modulation of the geomorphology of the critical zone. Forthcoming in *Earth Surface Processes and Landforms*.

Arbellay E, Stoffel M, Bollschweiler M. 2010. Dendrogeomorphic reconstruction of past debris-flow activity using injured broad-leaved trees. *Earth Surface Processes and Landforms* **35**: 399–406.

Bauch GD, Hickin EJ. 2011. Rate of floodplain reworking in response to increasing storm-induced floods, Squamish River, south-western British Columbia, Canada. *Earth Surface Processes and Landforms* **36**: 872–884.

Brook MS, Dean JF, Keys HJ. 2011. Response of a mid-latitude cirque glacier to climate over the last two decades: Mangaehuehu Glacier, Mt Ruapehu. *Earth Surface Processes and Landforms* **36**: 1973–1980.

Bullard JE. 2013. Contemporary glacigenic inputs to the dust cycle. *Earth Surface Processes and Landforms* **38**: 71–89.

Church M. 1996. Space, time and the mountain: how do we order what we see? In *The Scientific Nature of Geomorphology*, Rhoads BL, Thorn CE (eds). Wiley: Chichester; 147–169.

Clarke ML, Rendell HM. 2010. Climate-driven decrease in erosion in extant Mediterranean badlands. *Earth Surface Processes and Landforms* **35**: 1281–1288.

Clay GD, Dixon S, Evans MG, Rowson JG, Worrall F. 2012. Carbon dioxide fluxes and DOC concentrations of eroding blanket peat gullies. *Earth Surface Processes and Landforms* **37**: 562–571.

Colombera L, Bersezio R. 2011. Impact of the magnitude and frequency of debris-flow events on the evolution of an alpine alluvial fan during the last two centuries: responses to natural and anthropogenic controls. *Earth Surface Processes and Landforms* **36**: 1632–1646.

Doetterl S, van Oost K, Six J. 2012. Towards constraining the magnitude of global agricultural sediment and soil organic carbon fluxes. *Earth Surface Processes and Landforms* **37**: 642–655.

Dymond JR. 2010. Soil erosion in New Zealand is a net sink of CO_2. *Earth Surface Processes and Landforms* **36**: 1763–1772.

Harden T, Macklin MG, Baker VR. 2010. Holocene flood histories in south-western USA. *Earth Surface Processes and Landforms* **35**: 707–716.

Hilton RG, Meunier P, Hovius N, Bellingham PJ, Galy A. 2011. Landslide impact on organic carbon cycling in a temperate montane forest. *Earth Surface Processes and Landforms* **36**: 1670–1679.

Huggel C, Clague JJ, Korup O. 2012. Is climate change responsible for changing landslide activity in high mountains? *Earth Surface Processes and Landforms* **37**: 77–91.

Intergovernmental Panel on Climate Change. 2007. Erosion and sediment transport. In Climate Change 2007: Working Group II: Impacts, Adaptation and Vulnerability, IPCC, http://www.ipcc.ch/publications_and_data/ar4/wg2/en/ch3s3-4-5.html, accessed 08.10.2012.

Jones AF, Brewer PA, Macklin MG. 2008. Geomorphological and sedimentological evidence for variations in Holocene flooding in Welsh river catchments. *Global and Planetary Change* **70**: 92–107.

Korup O, Gorum T, Hayakawa Y. 2012. Without power? Landslide inventories in the face of climate change. *Earth Surface Processes and Landforms* **37**: 92–99.

Kuhn NJ, Hoffmann T, Schwanghart W, Dotterweich M. 2009. Agricultural soil erosion and global carbon cycle: controversy over? *Earth Surface Processes and Landforms* **34**: 1033–1038.

Layzell AL, Eppes MC, Johnson BG, Diemer JA. 2012. Post-glacial range of variability in the Conejos River Valley, southern Colorado, USA: fluvial response to climate change and sediment supply. *Earth Surface Processes and Landforms* **37**: 1189–1202.

Lewin J. 2013. Enlightenment and the GM floodplain. *Earth Surface Processes and Landforms* **38**: 17–29.

Leyland J, Darby SE. 2009. Effects of Holocene climate and sea-level changes on coastal gully evolution: insights from numerical modelling. *Earth Surface Processes and Landforms* **34**: 1878–1893.

Lu H, Mason JA, Stevens T, Zhou YL, Yi SW, Miao XD. 2011. Response of surface processes to climatic change in the dunefields and Loess Plateau of North China during the late Quaternary. *Earth Surface Processes and Landforms* **36**: 1590–1663.

Lu XX, Zhang S, Xu J. 2010. Climate change and sediment flux from the Roof of the World. *Earth Surface Processes and Landforms* **35**: 732–735.

Macklin MG, Lewin J. 2003. River sediments, great floods and centennial-scale Holocene climate change. *Journal of Quaternary Science* **18**: 102–105.

Macklin MG, Lewin J. 2008. Alluvial responses to the changing Earth System. *Earth Surface Processes and Landforms* **33**: 1374–1395.

Novara A, Armstrong A, Gristina L, Semple KT, Quinton JN. 2012. Effects of soil compaction, rain exposure and their interaction on soil carbon dioxide emission. *Earth Surface Processes and Landforms* **37**: 994–999.

Pawson RR, Evans MG, Allott TEHA. 2012. Fluvial carbon flux from headwater peatland streams: significance of particulate carbon flux. *Earth Surface Processes and Landforms* **37**: 1203–1212.

Petterson G, Renberg I, Sjostedt-de Luna S, Arnqvist P, Anderson NJ. 2010. Climatic influence on the inter-annual variability of late-Holocene minerogenic sediment supply in a boreal forest catchment. *Earth Surface Processes and Landforms* **35**: 290–298.

Savi S, Schneuwly-Bollschweiler M, Bommer-Denns B, Stoffel M, Schlunegger F. in press. Geomorphic coupling between hillslopes and channels in the Swiss Alps. Forthcoming in *Earth Surface Processes and Landforms*.

Silhan K, Brazdil R, Panek T, Dobrovolny P, Kasickova L, Tolasz R, Tursky O, Vaclavek M. 2011. Evaluation of meteorological controls of reconstructed rockfall activity in the Czech Flysch Carpathians. *Earth Surface Processes and Landforms* **36**: 1898–1909.

Thomas DSG. 2013. Reconstructing paleoenvironments and palaeoclimates in drylands: what can landform analysis contribute? *Earth Surface Processes and Landforms* **38**: 3–16.

Thomas T, Phillips MR, Williams AT, Jenkins RE. 2011. A multi-century record of linked nearshore and coastal change. *Earth Surface Processes and Landforms* **36**: 995–1006.

Tote C, Govers G, Van Kerckhoven S, Filiberto I, Verstraeten G, Eerens H. 2011. Effect of ENSO events on sediment production in a large coastal basin in northern Peru. *Earth Surface Processes and Landforms* **36**: 1776–1788.

Van Oost K, Cerdan O, Quine TA. 2009. Accelerated sediment fluxes by water and tillage erosion on European agricultural land. *Earth Surface Processes and Landforms* **34**: 1625–1634.

Verhaard PM, Biron PM, Ferguson RI, Hoey TB. 2010. Numerical modelling of climate change impacts on Saint-Lawrence River tributaries. *Earth Surface Processes and Landforms* **35**: 1184–1198.

Wainwright J, Millington JDA. 2010. Mind, the gap in landscape-evolution modelling. *Earth Surface Processes and Landforms* **35**: 842–855.

Worrall F, Rowson JG, Evans MG, Pawson R, Daniels S, Bonn A. 2011. Carbon fluxes from eroding peatlands - the carbon benefit of revegetation following wildfire. *Earth Surface Processes and Landforms* **36**: 1487–1498.